INORGANIC CHEMISTRY

Making cement and concrete nature’s way

Microbes figured out how to make these materials long ago. Industry is starting to catch on

by Mitch Jacoby

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Credit: Prometheus Materials | Stimulated by light, microbes in this bioreactor multiply and react carbon dioxide with calcium ions, forming calcite, a cement-like material.

IN BRIEF

Standard methods for making cement and concrete emit more than 8% of global anthropogenic carbon dioxide, require high temperatures, and consume massive amounts of energy. Various microbes secrete cement-like substances and form rock-hard materials—and they do so at room temperature via carbon-free biomineralization methods. Several start-ups and research organizations are working to harness these biological processes to produce green versions of bricks and other common construction products and to build concrete structures in environmentally friendly ways.

Mention the words *cement* and *concrete*, and most people will conjure images of heavy trucks, rugged roadways, and mighty bridges.

But not everyone. A growing number of people think of squishy bugs and microbial slime when they hear about hard-core construction materials. Those people—microbiologists, engineers, and entrepreneurs—are keen to show the world that concrete, which is used more than any other material on earth except water, can be manufactured in a sustainable way by tiny bugs. And they’re betting that it can be done efficiently and economically.

At first blush, there may seem to be little connection between bugs, biology, and bricks. But not to Mother Nature. “There are a wealth of examples in the natural world where biology makes tough, hardened materials for various purposes,” including structural support and protection, says Matthew Pava, a biologist and program manager with the US Defense Advanced Research Projects Agency (DARPA).

Animal bones, teeth, and shells rank among the most common examples of such materials. They are formed through biomineralization, a process in which living organisms combine elements from their bodies or the environment and precipitate minerals.

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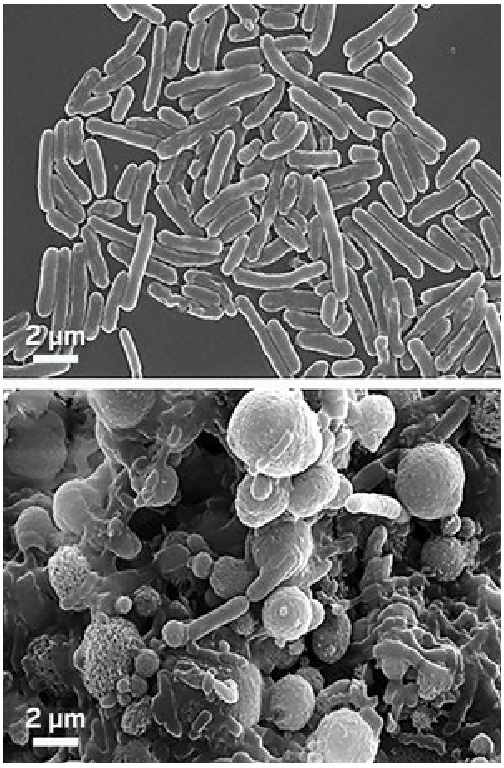
Various microorganisms also drive biomineralization. They secrete cement-like materials that can form biobased types of concrete. But unlike standard industrial processes for making cement and concrete, which require very high temperatures and emit massive amounts of greenhouse gases, the processes carried out by microbes run at ambient temperature and are emission-free. Biocement aficionados in a number of start-ups, as well as in academia and the military, are working to capitalize on these natural and environmentally friendly processes. Some are gearing up to produce green versions of cinder blocks, bricks, and other common concrete building products. Others are working on processes that deploy biobased concrete in places that are out of reach for the heavy trucks and machinery needed to deliver the conventional stuff.

CONCRETE’S HUGE FOOTPRINT

Concrete is arguably the most important manufactured material of the modern world. Roughly 30 billion metric tons of the synthetic rock is produced globally each year to build soaring structures such as bridges, dams, and high-rise buildings; ground-level walkways, roads, and highways; and underground tunnels and sewage systems.



Credit: *PLOS One* 2019, DOI: 10.1371/journal.pone.0210339

Under the right conditions, *Sporosarcina pasteurii* (top) cause carbonate and calcium ions to react, producing calcite on the microbes’ surfaces (bottom).

Production of the critical building material has risen sharply in recent years, as lower-income countries, particularly in Asia and Africa, have undertaken huge construction projects. And demand isn't subsiding. "Construction is predicted to double worldwide between now and 2060. That's the equivalent of building a new New York City every month for the next 36 years," says Loren Burnett, CEO of Prometheus Materials, a biocement start-up based in Longmont, Colorado.

Clearly, concrete's physical footprint is gargantuan and growing. The same is true of its environmental one. Manufacturing cement—the glue that binds the components of concrete—accounts for roughly 8% of the world's anthropogenic carbon dioxide emissions and consumes nearly 3% of its energy supply, according to the International Energy Agency. Concrete production is also responsible for roughly 9% of global industrial water use, according to a technical analysis (*Nat. Sustainability* 2018, DOI: 10.1038/s41893-017-0009-5).

Today's companies make the standard cement material used in construction worldwide—portland cement—by way of a process that has undergone little change since it was developed in England about 200 years ago. (The name comes from the resemblance of the material to stone quarried on the Isle of Portland in England.)

The process involves heating powdered limestone (composed mainly of calcium carbonate, $CaCO_3$) and clay (a mixture of alumina, silica, and other minerals) to 1,450 °C or higher in a rotating kiln. The high temperature drives calcination, a chemical reaction that converts $CaCO_3$ to calcium oxide (CaO), also called lime, and releases CO_2. Manufacturers grind the calcination product, which is known as clinker, with gypsum, a calcium sulfate mineral, to control the subsequent reaction with water.

To make building facades, bricks, and other concrete products, suppliers blend cement powder with sand and a mixture of gravel and crushed rock known as aggregate. They combine those materials with water, which triggers a series of hydration reactions, mainly involving calcium silicate compounds. The hydration reactions convert the cement powder to a pasty glue that binds concrete and ultimately hardens to form a strong, hard-as-rock solid.

TAKING THE BIOROUTE

Why go the bioroute? The short answer is that it's far kinder to the environment than the conventional one. CO_2 emissions that are directly related to standard methods of cement production fall into two categories: those caused by the calcination process and the ones related to fuel use, explains Danielle Beatty of the University of Colorado Boulder.

Credit: Prometheus Materials

Produced by microalgae, this biomineralized powder functions as biocement

Beatty, a materials science graduate student who works with biocement expert Wil V. Srubar III, explains that the CO_2 released when $CaCO_3$ is converted to CaO accounts for 60–70% of cement production's direct CO_2 emissions. That reaction is unavoidable in the standard method of producing portland cement but does not occur in the microbial version. The bulk of the remaining emissions (roughly 30–40%) comes from burning fossil fuels—often coal—to heat the kiln. Overall, cement manufacturing emits more than 800 kg of CO_2 for every metric ton of portland cement produced.

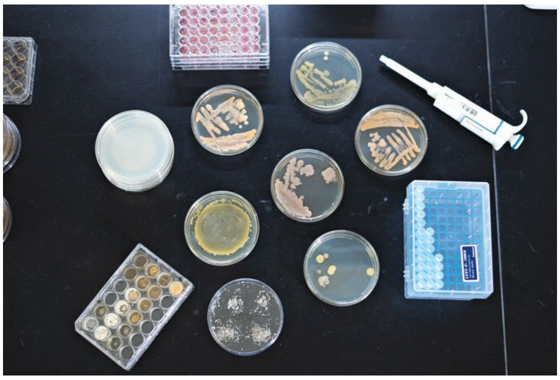
In contrast to these energy-intensive and greenhouse gas-emitting processes, the ones used by various biocement-making bacteria, algae, and microbes are mild and environmentally friendly. "Mother Nature is the best biotechnologist," says Stephen Bell, director of biotechnology at Prometheus. "We mimic what she figured out to do over the course of evolution and use that technology to make our materials on a commercially viable timescale."

Recently, the company raised $8 million in series A funding for its bioprocess for making cement. Burnett says the company's pilot plant is making "limited quantities of biocement-based blocks" and has received ASTM certification for load-bearing and non-load-bearing blocks. Now the company is working on scaling up production of cinder blocks, roofing tiles, and other precast products.

BIOMINERALIZATION BASICS

The busy bugs working day and night at the Prometheus facility belong to a family of cyanobacteria, photosynthesizing organisms also known as blue-green algae or microalgae. The microbes are held in water-filled bioreactors that contain nutrients necessary for them to grow and multiply. The reactor also contains a supply of CO_2 and calcium ions, which the microscopic bugs convert to calcite, a form of calcium carbonate that serves as biocement.

In the current setup, light-emitting diodes (LEDs) illuminate the reactor to drive photosynthesis. But the company's future plans call for operating the reactor outdoors in sunlight, eliminating the need for electricity to power the LEDs, according to Bell.



Credit: Biomason

Researchers specializing in biomineralization use the tools of biology to make cement and concrete.

After spending a few hours in a bioreactor, the growing microbes are transferred to a large vat containing a proprietary solution that accelerates biomineralization. The company blends that product with sand, aggregate, and water and pours the bioconcrete mixture into a commercial masonry machine that forms cinder blocks and other products.

Blue-green algae aren't the only bugs in the business. North Carolina-based Biomason, a company with roughly 85 employees, enlists bacteria to do its biocement bidding. Much of the company's focus is on *Sporosarcina pasteurii*, a nonphotosynthesizing bacterium, according to Michael Dosier, Biomason's chief technology officer.

S. pasteurii has been thoroughly studied by many research groups investigating biomineralization methods for making construction materials. That topic is covered in detail in a recent review paper by University of Colorado scientists Beatty, Srubar, and Sarah Williams, a postdoctoral associate in Srubar's group (*Annu. Rev. Mater. Res.* 2022, DOI: 10.1146/annurev-matsci-081720-105303).

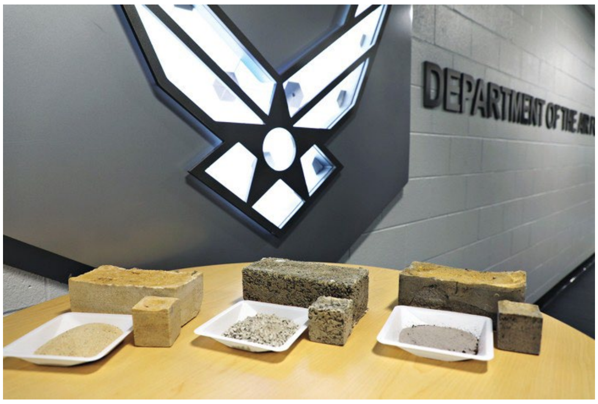
S. pasteurii's mode of operation stems from its production of urease, an enzyme that hydrolyzes urea ($CO(NH_2)_2$). The hydrolysis reaction ultimately produces carbonate ions (CO_3^{2-}) and ammonium (NH_4^+) ions. Carbonate ions react in the presence of calcium ions to produce calcite in an overall process known as microbially induced calcite precipitation.

APPLICATIONS ABOVE GROUND AND BELOW

Biomason manufactures a line of precast concrete products under the name Biolith. The company says its masonry tiles outperform those made from standard materials in terms of compressive strength, resistance to freeze-thaw damage, and other physical properties that could limit durability.

The Biolith pavers made in Biomason's first production run were used in 2015 to construct two pedestrian patios for the file-hosting company Dropbox at its headquarters in San Francisco. Biomason continues to grow. Last year the company announced that it raised $65 million in series C funding. And according to Dosier, Biomason just built a manufacturing line in Ikast, Denmark, in partnership with the Danish concrete giant IBF to ramp up production of the tiles.

Those developments come as other companies are also getting into the biocement business. For example, Srubar recently cofounded Minus Materials to commercialize a microalgae-based process for making bioconcrete. And Bind-X, another start-up capitalizing on microbially induced calcite precipitation, set up shop near Munich.



Credit: AFRL

As is the case for standard bricks, properties of these bioconcrete bricks can be tailored by using various types of sand and aggregate.

Applications for bioconcrete extend far beyond typical ones for pavers, cinder blocks, and other precast products. To simplify logistics, the US Air Force wants to use the technology to quickly build runways and concrete platforms in the middle of nowhere.

Credit: Biomason

The bricks in this Raleigh, North Carolina, patio are made of biocement.

“We are working with Biomason to see if we can apply this technology in remote field locations to make infrastructure without having to transport a ton of equipment, machinery, and materials,” says Maneesh Gupta, a research group leader at the Air Force Research Laboratory at Wright-Patterson Air Force Base in Ohio. The idea, Gupta explains, is to develop a ready-mix version of bacteria so field engineers can add water, urea, and calcium chloride and spray the solution onto loose soil, sand, or rock to build pavement where it’s needed.

That technology could be used in locations without airfields to form a layer of hardened sand that prevents hazardous and blinding dirt clouds from being kicked up as helicopters land. Or fast-forming bioconcrete could extend the usable area at an existing airfield for operating heavy vehicles and unloading cargo planes in a disaster-relief situation. And unlike ordinary robust concrete roads and walkways, the thin layer of bioconcrete laid down for these types of applications can be removed easily, returning the ground to its original condition.

“When we work with a country on a short-term operation, they may not want us to build infrastructure that’s going to last for 30 years or longer,” Gupta says. “When it’s time to leave, we may need to put things back the way they were before, take our stuff, and go.”

In a particularly green proof-of-concept demonstration, a study led by researchers at Nanyang Technological University showed that biocement can be made from waste materials. Specifically, the scientists used industrial carbide sludge (a source of calcium ions) and urea from the urine of mammals to mediate microbially induced calcite precipitation. Then they used that material to turn sand into rugged bioconcrete. The waste-based process is now being evaluated for its efficacy in controlling beach erosion (*J. Environ. Chem. Eng.* 2022, DOI: 10.1016/j.jece.2022.107443).

An entirely different application exploits microbes’ biomineralization talents far below ground. Montana-based BioSqueeze uses the biological process to seal oil and gas wells that are leaking methane into the atmosphere from 1,000 m below. Methane has a far higher global warming potential than CO_2—86 times as high, by some estimates.

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Randy Hiebert, the company’s vice president for R&D, explains that these wells are generally constructed from a set of long concentric steel tubes (casings), and the space between the casings is filled with concrete to prevent leaks. Eventually, however, tiny fractures in the concrete—or pores in the below-ground rock formations—allow gas to permeate to the surface. To plug those leaks, BioSqueeze pumps a biomineralizing solution deep into the well and lets the microbes do their thing.

Adrienne Phillips, a specialist in biofilms at Montana State University and a longtime collaborator of Hiebert’s, points out that the bacteria typically used in this application, *S. pasteurii*, are on the order of 1–3 μm in diameter. Because of their small size, she says, they easily wend their way into microscopic cracks, form sticky biofilms, and precipitate calcite, which seals the fractures.

BioSqueeze sealed its first oil and gas well in 2019. Since then, the firm, now with 24 employees, has successfully remediated over 100 leaking wells in nine states and two provinces in Canada.

Biocement and bioconcrete aren’t new materials. Nature has been making them for eons. But humans have only just started working with them. So far, so good. “We’re still looking for new ways to capitalize on these natural production processes and tailor them to our advantage,” DARPA’s Pava says. It’s tough to predict what new applications will unfold for these biominerals. It’s a safe bet, however, that they’ll be friendly to the environment.

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